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PHYSICS CONCEPT MAPS

**ANALYSIS ON COHERENT KNOWLEDGE STRUCTURES
IN PHYSICS TEACHER EDUCATION**

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ACADEMIC DISSERTATION

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ABSTRACT

In physics teacher education the use of graphical knowledge-representation tools like concept maps are often used because they are known to support the formation of organised knowledge. It is widely assumed that certain structural characteristics of concept maps can be connected to the usefulness of content. In order to study this relationship, the concept maps made by pre-service physics teachers are examined here. The design principles of the concept maps are based on quantitative experiments and modelling as the basic procedures in physics concept formation. The approach discussed here is informed by the recent cognitively oriented ideas of knowledge organisation around basic knowledge-organisation patterns and how they form the basis of more complex concept networks. The epistemic plausibility of justifications written in links is evaluated by using a four-level classification introduced here. The new method generalises and widens the existing approaches which use concept maps in representing the learners' knowledge, and which also use concept maps for research purposes. Therefore, this thesis presents some novel theoretical constructs for analysis and discusses empirical results by using these new constructs at length, in order to show the advantages which the new theoretical aspects offer. Modelling of the data shows that such a concept-mapping technique supports students' conceptual understanding. Also their usefulness in making plans for teaching is identified through modelling the flux of information which the relational structure of the map represents.

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following publications:

- I** Koponen, I., & Pehkonen, M.* (2010). Coherent Knowledge Structures of Physics Represented as Concept Networks in Teacher Education. *Science & Education*, 19:259–282.
- II** Nousiainen, M., & Koponen, I. (2010). Concept Maps Representing Physics Knowledge: Connecting the Structure and Content in the Context of Electricity and Magnetism. *Nordic Studies in Science Education*, 6, 155–172.
- III** Nousiainen, M. (2012). Making Concept Maps Useful for Physics Teacher Education: Analysis of Epistemic Content of Links. *Journal of Baltic Science Education*, 11(1), 29–42.
- IV** Nousiainen, M., & Koponen, I. (2011). Pre-service Physics Teachers' Concept Maps Representing Relational Structure of Physics Concepts. *Journal of Baltic Science Education*, 10(3), 183–194.
- V** Nousiainen, M., & Koponen, I. (2011). Knowledge Organization in Concept Maps: Teacher Students' Representations of the Relatedness of Physics Concepts. In J. Filipe & L.G. Dietz (eds.) *KEOD 2011, Proceedings of the International Conference on Knowledge Engineering and Ontology Development*. SciTecPress, Lisbon, Portugal, pp. 139–144.

The publications are referred to in the text by their roman numerals. The contributions of the author of this dissertation to the publications are as follows. **I**: The author had a central role in planning of the research and in setting up the research design and was mainly responsible for the data analysis. The author also participated in the writing of the article. **II**, **IV** and **V**: The author had a major role in planning the research and in the setting up of the research design and was mainly responsible for the data analysis. The author had a major role in the writing of the articles. **III**: The author alone was responsible for planning and setting up the research, analysing the data, and constructing and writing the article. Article **V** is published in established proceedings-series, where the rejection rate is usually 70% (publisher's announcement).

* Pehkonen is the author's former last name.

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1 INTRODUCTION

In physics teacher education, one of the recurrent themes is the importance of fostering the formation of organised and coherent knowledge structures. First and foremost this means that teachers need to have such an understanding of the relatedness of physics concepts that they can introduce the physics concepts in an ordered and logical way in their teaching, so that there is continuity of teaching. In addition, contingency is important: there are always many possibilities to proceed in teaching. Although this is a shared goal of most educators and researchers, there seems to be no simple, shared understanding of what such organised and coherent teachers' knowledge may actually mean, how it can be recognised and what kinds of representational tools there are for explicating such knowledge.

Coherence and contingency are not a self-explanatory or unambiguous attribute of organised knowledge and they need to be specified so that they could be related to the structure of knowledge organisation. In order to make a meaningful statement of contingency and coherence, or their lack, one should be able to give some structural characteristic of them (cf. diSessa 2008; Thagard 2000). In this thesis, the contingency and coherence of knowledge are connected to the relations between concepts, and on this basis, the degree of contingency and coherence of pre-service teachers' views are discussed. The original research articles **I-V** in this thesis show how suitable measures for coherence and contingency of knowledge can be developed step-by-step using concept maps as a representational tool.

Concept maps provide one promising tool representing the organisation of knowledge and for better defining what coherence of organised knowledge may mean. There is a vast body of educational research about the use of concept maps in teaching and learning, which suggests that a good understanding and a high quality of students' knowledge is reflected in concept maps as structures which are tightly connected and web-like (Derbentseva, Safayeni and Cañas 2007; Kinchin, Hay and Adams 2000; Kinchin, De-Leij and Hay 2005; Liu 2004; Safayeni, Derbensteva and Cañas 2005), or which are hierarchically organised (Novak and Gowin 1984; McClure, Sonak and Suen 1999; Novak 2002; Ruiz-Primo and Shavelson 1996). These notions implicitly address the question of the coherence of a conceptual system, as it becomes represented in the form of a concept map. Similarly, the question of the validity of knowledge as it is represented in the students' concept maps has been the topic of many investigations, where different methods have been proposed to evaluate the validity of the knowledge contained in the maps (McClure et al. 1999; Novak 2002; Ruiz-Primo and Shavelson 1996; Nicoll, Francisco and Nakhleh 2001). In the above-mentioned traditional studies the acceptability of the conceptual system (in form of a concept map) as a whole depends on the direct sum or

average of the acceptability of individual conceptual elements (pairwise relations between concepts or single propositions) rather than on a more holistic view of the connectedness and the type of connectedness of the whole system.

Concept maps are of course only one way to represent the relations between concepts and they have restrictions (e.g. only connections, which are represented in pairs) but they are flexible enough for expressing many important features and types of relations between concepts. The coherence of pre-service teachers' views are then analysed on the basis of the maps by using the notion of conceptual coherence (Thagard 2000) as the background theory of defining and embodying the notion of coherence. The basic developments of this approach are reported in articles **I-III** and **V**. Article **IV** reports how such an approach can be used to monitor changes in students' conceptual understanding. The contingency, which relates to different available paths to introduce new concepts, requires paying attention to the ordering and directedness of relations, which is done in article **V**.

The new approach introduced here is based on the method of representing the connectedness and relatedness of concepts as node-link-node structures in the form of concept maps. The node-link-node structure forms the skeletal framework, in which the acceptability of each link can be discussed in detail by using the four criteria for epistemic analysis introduced in this thesis (article **III**), and how the overall conceptual coherence of the map can then be evaluated. The analysis of the overall conceptual coherence is done on the basis of the network approach so that topological measures which characterise the conceptual coherence are formed and calculated from the maps. Such measures depend then on the acceptability of individual links and on the overall structure of the maps; conceptual coherence arises equally from the acceptability and from the structure. The results are presented in a way which explicitly shows how the degree of coherence becomes affected by the epistemic acceptability of links. A high degree of coherence is acquired when the highest criteria for acceptability are fulfilled and the lowest degree of coherence when acceptability is low. However, the relation between acceptability and coherence is not linear, and even with a substantial number of low acceptability links coherence may remain high. This shows the robustness of coherently connected conceptual systems.

The analysis method for coherence can be used to analyse the students' knowledge organisation as they represent it in their concept maps, as shown in detail in articles **I-III** and **V**. In addition, the analysis method can be applied to monitor the students' development in organising their knowledge, and to recognise (at least tentatively) the students' "proximal zone of development", as discussed in article **IV**.

The concept maps also contain information on the contingency of the relatedness of concepts, which is an important component in providing the logic of progression in introducing new concepts in different possible ways. As such, it is an important aspect of well-ordered teaching, which always

needs to provide more than one possible way to make progress. The recognition of this property requires developing analysis methods which go beyond coherence, and attention needs to be paid to the ordering and the directedness of relations. This is done in article **V**, which also addresses the relation of directedness to the ordered planning of teaching.

The methods developed in this thesis have been applied in the practical teaching of pre-service teachers in two courses, in the teacher education unit, Department of Physics, University of Helsinki. The feedback from students has shown that the teaching solutions based on both the concept maps and paying attention to coherence and contingency of knowledge is beneficial and is also found to be useful by students. In future, further developments in teaching will utilise substantially the methods developed and reported in this thesis.

2 COHERENCE AND CONTINGENCY OF KNOWLEDGE IN TEACHING AND LEARNING

The question of the organisation of scientific knowledge is closely related to the ways knowledge is acquired and justified. The ways that concepts are used ties them together, provides meaning and eventually leads to an interwoven network of concepts where they are related. Consequently, concepts can be seen as elements of complex, network-like structures where a special role is given to interrelations between concepts, and where these interrelations carry the epistemic credentials of the concepts. This leads to the notion that, in order to discuss the coherence of knowledge, the structural relations between the concepts need to be referred to and, on the other hand, much of the epistemic justification of the knowledge hinges on the coherence of such systems.

2.1 COHERENCE AND OBSERVATIONS

Coherent knowledge alone may still, however, be unreliable, inapplicable and not conforming to observed features of real phenomena (i.e. not true). In the philosophical literature, this is sometimes referred to as the correspondence problem of the coherence theory of truth (Thagard 2000; BonJour 1985). Although here the purpose is not to engage in a philosophical discussion of the coherence theory of knowledge, it is clear that a similar kind of “correspondence” problem as in the coherence theory needs to be faced. Attention must be paid to relations between the conceptual elements of knowledge structures and how the conceptual elements are related to the observed facts. One possible solution is based on the notion that when coherent knowledge also gives a coherent explanation of real phenomena or real observations, a relation between the conceptual system and real system must exist (i.e. there is correspondence). This type of coherence, which gives a special role to observations and experiments and their explanations, has been called explanatory coherence (Haack 1993; Thagard 1992; BonJour 1985). Explanatory coherence ensures that a conceptual system can be used in giving explanations and making predictions of observed features of real systems, and always in a way where the use of concepts is systematic and symmetric in the sense that they retain their mutual dependencies and relations in different situations. This kind of a coherent conceptual system carries the epistemic credentials of “true knowledge”.

It may appear somewhat unusual that coherence and correspondence are combined, but this is also what is found in BonJour’s (1985) and Thagard’s accounts of the coherence of knowledge. In this case, the coherence of the

conceptual system depends on the acceptability of connections, and the norms of such acceptability are based on correspondence. On the other hand, the overall epistemic justification of the system and its parts depend on the overall coherence (for similar arguments, see Thagard 2000 and BonJour 1985).

2.2 CONCEPTUAL COHERENCE

The question about the relatedness of concepts is a question of conceptual coherence, where the cohering elements are concepts instead of propositions (Thagard 2000). In this thesis, the elements which cohere are concepts, and their relations are based on specific types of situations (experiments and models) where the concepts can be applied. Following Thagard (2000), this case should be termed conceptual coherence. However, conceptual coherence entails many aspects that are similar to explanatory coherence and many issues within explanatory coherence and conceptual coherence are, in turn, similar (Thagard 2000). Here we are concerned only with two types of situations where conceptual coherence arises: using concepts either in context of describing or explaining the outcomes of experiments, or using concepts as parts of models which describe experimental results, or which generalise those results. These instances provide the basic connections between the concepts. If the use of concepts is acceptable, the relation (or constraint) is positive, if it is not acceptable, the relation is taken simply as nonexistent instead of negatively constrained. The normative criteria for the acceptability are defined separately, and the role of these norms is to provide the correspondence with real systems.

The justification behind this restriction to experiments and models is the notion that, in teaching and instruction of physics, these are central procedures connected to the construction and use of physics knowledge (article I). The experiments discussed here cover laboratory experiments and the explanations which are given to the data produced in such experiments. In this case it is evident that the concepts become connected through the methods of designing experiments, through interpretation of experiments and through exemplifying how the experiments are used to justify knowledge (in a school context). In school instruction and learning, coherence is established through instruction and argument, rather than through discovery. From the point of view of physics teaching and instruction the most interesting experiments are the so-called quantifying experiments, where the concept is operationalised and made measurable through pre-existing concepts. Although there are many different types of experiments that are relevant for teaching and learning, the quantitative experiments arguably have a very special role in teaching and learning physics (Koponen and Mäntylä 2006; article I).

Conceptual coherence is also closely related to the use of models and modelling. The most common way to use models in physics teaching is namely a deductive way of providing explanations and predictions. Model construction is carried out with comprehensible rules subordinated to higher level theory, and the constructed models are then validated by matching them with experimental results (see Koponen 2007; Böttcher and Meisert 2010). Using models in this way, concepts become related quite naturally through their use in model relations.

Coherence in the above sense requires that the concepts are repeatedly connected not only to each other but also to observed properties of phenomena as they appear in experiments. It should be noted that such relations are symmetric so that if concept A coheres with B, also B coheres equally with A. In practice, these types of connections give rise to simple basic patterns and can be conveniently represented in the form of undirected concept maps. However, before these basic patterns and their representation as maps is discussed in more detail, attention needs to be paid to the norms of accepting the positive relations between concepts so that the degree of acceptability (ranging from 1 to 4) i.e. the “strength” of the connection between concepts can be estimated (article III).

2.3 CONTINGENCY OF KNOWLEDGE

Contingency of knowledge refers here to the different possibilities how concepts are successively related to each other, thus providing different and alternative ways to introduce concepts by using the support of already known concepts. Coherence and contingency are both important aspects of scientific knowledge, expected to increase when the body of knowledge expands (Scheibe 1989).

In teaching and learning, contingency answers to the questions as to how and in how many ways new concepts are introduced and justified on the basis of concepts which have already been learned. This kind of knowledge is valuable for the teacher, because it is an important part of the teacher’s, as well as the learner’s, conceptual knowledge (Tiberghien 1994; Duit, Gropengießer and Kattmann 2005). In order to construct teaching approaches and plans, where content knowledge is properly organised, the teacher needs to know how the concepts can be introduced in teaching in a logically justified manner. The well-organised content for teaching physics can be recognised from some very basic features: Clear exposition of new concepts, clear direction of progress, and clarity in how concepts become related. Consequently, the connections which tie concepts to each other quite naturally provide a comprehensible direction for progress – there is “flux of information” so that what was learned before is the basis for learning new ideas. This kind of inherent logic is a pre-requisite for providing a solid structure and sound basis for physics teaching, and it prevents content from

breaking into disconnected and unrelated pieces. The organisation of physics knowledge and the logical progression in the ways the concepts are introduced needs, however, suitable resources for making these aspects visible and recognisable in pre-service teachers' representations (article **V**).

3 KNOWLEDGE ORGANISATION REPRESENTED BY CONCEPT MAPS

Concept maps are widely used in the teaching and learning of physics (Ingeç 2009; van Zele, Lenaerts and Wieme 2004; Vanides, Yin, Tomita, Ruiz-Primo and Shavelson 2005), chemistry (Zoller 1990; Nicoll et al. 2001) and biology (Kinchin et al. 2000). They are also often used as tools of assessment and evaluation in learning (Ruiz-Primo and Shavelson 1996; van Zele et al. 2004; Yin, Vanides, Ruiz-Primo, Ayala and Shavelson 2005). For the assessment and evaluation of concept maps there are many well-established techniques. However, these techniques (when quantitative) are still too limited by their scope, and if not limited (when qualitative), they are too ambiguous.

The structural quality of concept maps has traditionally been approached by counting the hierarchical levels produced by the node-link-node connections and the number of cross-links within a given hierarchical level. This research approach pays attention to how concepts are interconnected locally, or pays attention to what the “semantic fields” provided by these connections are (Novak and Gowin 1984; Ruiz-Primo and Shavelson 1996; McClure et al. 1999; Nicoll et al. 2001). These kinds of methods have two severe shortcomings, however. First, the decision of the “hierarchical levels” is most often made on the basis of interpretative analysis. The validity and reliability of the interpretative analysis is then assessed through comparing results of two or more interpreters. Such agreement ensures that rules to detect the hierarchical levels are consistently followed, but it does not yet tell how valid and reliable the rules themselves are in discerning the desired structural aspects. Second, the measures based on the hierarchical levels and cross-links invariably depend on the density of links, so that maps with greater density of links per node are nearly always better ones.

As an alternative to the quantitative assessment, many qualitative methods of evaluation have been suggested (Vanides et al. 2005; Yin et al. 2005; Ingeç 2009; van Zele et al. 2004; Kinchin et al. 2000; Safayeni et al. 2005; Derbentseva et al. 2007; Liu 2004). Such qualitative methods for analysing the concept maps have revealed that global topological features, that are chain-, spoke- or web-like, carry important information about the quality of knowledge represented in the maps but that they cannot be easily captured by the quantitative methods of analysis (Kinchin et al. 2000; van Zele et al. 2004). However, the validity and the reliability of existing qualitative methods is difficult (if not even impossible) to assess, because the criteria of being “complex” or “web-like” is based on visual inspection only.

In this thesis a new quantitative method for analysis of the concepts maps is introduced (articles I-V) so that the important global topological features can be captured and measured. The method of analysis and the data models

introduced here make it possible to describe the complex topological features of the concept map, and which eventually enables the assessment of the maps on the basis of their connectivity (richness of content) and their structural quality.

3.1 RESEARCH QUESTIONS

The research questions which are pursued through articles **I-V** and which thus form the basis of the thesis can be roughly summarised in the following three questions;

1. What kind of structural features characterise organised knowledge structure?
2. How can the content of concept maps be analysed?
3. How can the collected data be modelled to give information of students' development in ordering their knowledge?

Each research question splits into more detailed questions as presented in the articles. Research question 1 is discussed in articles **I** and **II**. Research question 2 is answered in articles **I-III** and research question 3 in articles **IV** and **V**. In summary, the research is carried out as follows; first, coherence of knowledge is connected to knowledge structures and characteristics of such knowledge are identified. These features are then operationalised so that they can be measured from the concept maps. Second, the content of concept maps is analysed and structural analysis is connected to content analysis. Then it is possible to observe how much changes in structure and content contribute on the changes concept maps' quality. Third, modelling of data enables us to monitor students' abilities and achievements in organising their knowledge.

3.2 DESIGN PRINCIPLES FOR CONCEPT MAPS

Design principles discussed here rest on the use of quantitative experiments and models which are the traditional and important parts of procedural knowledge as discussed in school science (see article **I** and references therein). In the quantitative experiment, the concept is operationalised, that is, made measurable through pre-existing concepts. For example, the operationalisation of Coulombs' law (as discussed in detail in article **II**) requires the concept of force and charge, whereas the concept of the electrical field rests on force, charge and Coulomb's law, and so on. This mutual dependence of concepts means that a network of concepts is woven through

operationalisation. In such experiments, a new concept or law is always constructed sequentially, starting from those that already exist, and which therefore also provide the basis for an experiment's design and interpretation.

In addition to experiments, models are also core components of knowledge structures. For example, the definition of the electrical field (for details, see article **II**) can be seen as a model which interprets the force between two interacting charges into one part which causes the field (the charge as a source) and another part which experiences the field (the other charge). Another example is the model of a homogeneous field, extensively used as a model in introductory electricity courses. Typically, a model may be an idealised and symbolic representation or a description of dependencies found in an experiment or that should provide explanations and predictions of regularities found in experimental data (Koponen 2007; Sensevy, Tiberghien, Santini, Laube and Griggs 2008).

The use of experiments and modelling as linking procedures makes a close connection to a recent study about the steps involved in didactical reconstruction of knowledge construction where experiments and modelling processes are combined to produce new conceptual knowledge (Mäntylä 2011). The way the procedural knowledge becomes coded in the links in concept maps studied here takes place much along the same lines as described by Mäntylä. However, here in the construction of concept maps that method is simplified to a few basic steps, which form the basis of design principles to be introduced next. Consequently, the design of concept maps discussed here is based on a special type of selection of concepts and special types of links connecting the concepts. The “concepts” in the map can be:

1. Concepts or quantities.
2. Laws.

Of these elements, laws could be taken as particular experimental laws or law-like predictions in specific situations (derived from a theory). General laws are more fundamental principles (e.g. principles of conservation). In both cases, laws can be expressed as relations between concepts. The links are thus:

3. Experimental procedures (an operational definition).
4. Modelling procedures, which can be deductive models or definitions in terms of model-type relations.

The basic idea is that the design principles guide the construction process of the map. It should be noted that students must ensure that every link they draw on the map is a procedure (either experimental or modelling) and justify them separately. The design method reported in the present thesis was first developed by the author for the purposes of the physics teacher training courses 2007-2008 and with gradual improvements it has been in use in physics teacher training courses since 2008. In practise, it has given students a framework to develop their conceptual understanding. Results related to the practical use of the maps are discussed in more detail in articles **IV** and

V, and the student feedback about the use of the maps is reported in article III. The evaluation method reported in this thesis has never been in use as a practical evaluation method on the courses, but it has essentially guided the way the students' maps have been graded.

3.3 STRUCTURE OF CONCEPT MAPS

The procedures of experiments and modelling are central in providing the context where concepts are connected. Therefore, they are also central in providing the basic structural patterns of the network of concepts. In this thesis the major vehicles for the introduction of new concepts are the (quantitative) experiments, or alternatively descriptive or explaining models. This, of course, is more or less the situation how the physics conceptual system is approached in school teaching. Linking concepts through these procedures is the design principle of the concept maps (see the educational motivation and more details in article I). It is natural to assume that when the procedures of the experiments and modelling are used as a design principle to construct concept maps these design principles also play an important role in conferring the structure of concept maps.

The experiments discussed here are *operationalising experiments*, which are frequently used in advanced-level physics instruction. In this case the concept is operationalised (i.e. made measurable through pre-existing concepts) and the new concept is constructed sequentially, starting from the already existing ones which provide the basis for an experiment's design and interpretation. For example, Ampere's experiment and quantification of current and force between current carrying wires (for a more detailed discussion, see article II). Due to this interdependence between concepts contained in this procedure (force and current), they cohere symmetrically. In the simplest case of three concepts basic triangular covariation pattern is created between the concepts. The role of this triangular pattern is discussed in more detail in articles I and II.

The *modelling procedures* also create triangular patterns. This is related to the fact that many of the modelling procedures sequentially use existing concepts to produce a better understanding of the use of a concept or to define it better. The already existing concepts or principles are used to model a certain situation (e.g. through idealisation) so that new concepts become hypothesised and then become connected to the original ones through the modelling procedure. As an example of this kind of triangular connection, electrical field is discussed in article II.

These two procedures give rise to simple triangular-type patterns and combinations of them, which come in the form of different cycles. In addition, the concepts of the network always contain branches. The simplest of these branches is two-branched pattern, where three nodes are connected by two links. In Figure 1 some examples of such patterns are illustrated.

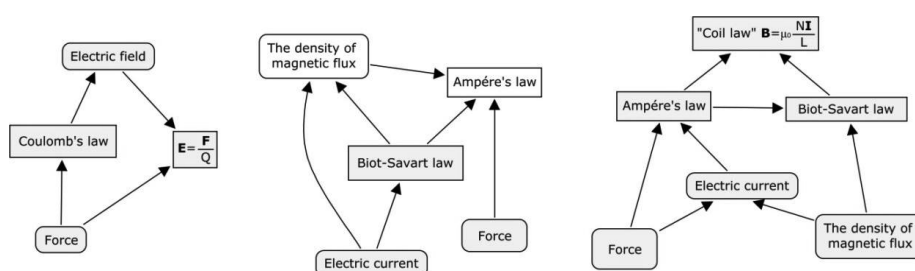


Figure 1 The hierarchical patterns and cycles can be identified as a combination of triangular patterns.

These basic patterns are the key elements in both the construction of concept networks and giving the network its overall organisation and, ultimately, providing coherence. The directedness of the connections and the different ways they branch, on the other hand, provides the contingency and thus the possible directions of the progress of the whole network. As will be seen, such patterns are easily recognised from students' concept maps representing the network of physics concepts. In all cases, the triangular pattern is quite central but also larger cycles are common.

The structural features of a well-organised knowledge structure (i.e. hierarchical ordering and local clustering-like interconnectedness) are those essentially brought forward by qualitative analysis of concept maps (cf. Kinchin et al. 2000; Kinchin et al. 2005; van Zele et al. 2004). On the structural level, all these qualitative notions can be operationalised and made quantitative as it has been discussed in more detail in articles I and II. The exact mathematical definitions for the variables are presented in section 4.3.

The epistemic acceptability of each link can be analysed and the structural role of links can be represented in terms of knowledge-ordering patterns. This also provides the means to evaluate the total acceptability of knowledge represented in the form of a concept map. The total outcome of the acceptability analysis is affected at the same time by the global structure (the topology of connections) and the acceptability of each single link. This means that the overall resulting network of concepts and the knowledge it represents can then be discussed in terms of coherence in regard to its structure as well as its content.

3.4 ACCEPTABILITY OF LINKS

Good organisation of knowledge is a prerequisite for coherence, but the connections lying behind that organisation need to be acceptable and valid connections in order to represent reliable knowledge. Validity criteria of knowledge are closely related to the argumentation supporting knowledge

because good justification can be associated with a chain of arguments, which hold on closer scrutiny and which are supported by evidence. Such validity criteria of argumentation within science education have recently been discussed by Sandoval and Millwood (2005). From the viewpoint of acceptability and validity of knowledge, one central aspect is the argumentation's potential to support the development of reasoning, particularly the choice of theories or positions based on rational criteria. The acceptability criteria of knowledge can be supported by argumentation since it includes reflection, justification, commitment to evidence and critical thinking (Jiménez-Aleixandre and Erduran 2008). These commitments to evidence have an important role also in establishing the coherence. A similar position is discussed by BonJour (1985) in terms of "observational priority" and by Thagard (2000) as "data priority", which is central for providing the correspondence with real phenomena. Through the argumentation, in this manner, the acceptability of knowledge, the formation of structure and the coherence of knowledge are all connected; acceptability and coherence provide the credentials of valid justification. Although here the main interest does not lie directly on argumentation, there are many common points worth noting between the present work and argumentation as it is discussed in recent educational literature. The most evident parallelism is found in the way the rational chain of reasoning is constructed and supported through argument.

The basis of argumentation analysis is discussed by several authors who have developed rating methods for the epistemic aspects of the argumentation (Sampson and Clark 2008; Kelly and Takao 2002; Sandoval and Millwood 2005). The analysis of arguments is discussed for instance by Kelly and Takao (2002), who note that the epistemic argumentation model can be used as a methodological tool as they present an epistemic argument structure, as well as by Kelly, Regev and Prothero (2008), who introduce credentials to assess written reasoning. In a similar way, Sampson and Clark (2008) discuss how Toulmin's (1958) scheme can be augmented and generalised to an analytic framework to assess and characterise the nature or quality of scientific arguments. Sampson and Clark (2008) highlight two different approaches to the classification of argumentation schemas: domain general or domain specific frameworks. The latter type of framework can be divided into two subcategories: arguments specific to science (content and justification) and arguments specific to epistemic levels of knowledge. However, in the present work (article **III**) attention is paid only to the epistemic aspects.

When discussing the viewpoint of assessing argumentation, Krathwohl (2002) provides an interesting contribution as he presents a revision to Bloom's taxonomy of educational objectives (Bloom 1956). In addition to cognitive processes, the revision contains four dimensions for knowledge: factual, conceptual, procedural and metacognitive knowledge. These ideas offer a promising line in setting up criteria for an epistemic analysis to assess

the rational chain of reasoning. With small modifications to the revised taxonomy, the epistemic analysis is here suggested to proceed in dimensions for 1) ontology, 2) facts, 3) methodology and 4) valid justification. The criteria are such that they are nearly self-evident pre-requisites for acceptable knowledge in physics. Therefore, these four criteria form a suitable basis for the analysing of epistemic acceptability of links as it follows.

1. Ontology. Ontological knowledge refers to ontologically correct entities and the concept referring to them are used, for example, in the case of particles (with the property of mass, charge etc.) and fields (with the property of extension, strength etc.). Ontology requires also that such concepts are correctly related. For example, in classical physics particles create fields but fields do not create particles. This means that concepts are linked in a logical way in the sense that they are presenting standard physics.

2. Facts. Factual (or declarative) knowledge consists of understanding about concepts, laws, principles and other types of relations and here it means the primary ability to identify and remember the meaning of concepts which is a pre-requisite for the utility of concepts. Making a correct factual statement thus requires that appropriate and correct quantities and laws are presented and that they are established on an ontologically correct basis. Factual knowledge forms the basis for students to handle the given concept mapping task in the sense that the most elementary structure of maps consists of nodes (concepts) and the connections between them represent factual knowledge. One should be able to know the facts (experimental or theoretical) which are relevant for connection between concepts. It should be noted that knowing the facts does not yet mean that it is possible to give a proper argument of how the connection is established in the procedural level; in some cases students were only able to state that a connecting relation exists, but were not able to tell about its form or content. Of course, factual knowledge is contained in all other, more sophisticated links where also the procedure of forming new concepts is described since factual knowledge forms the bedrock of more advanced knowledge.

3. Methodology. Procedural knowledge can be understood as the ability to perform certain things, it can be acquired through its application, and expertise can be seen as production of “if-then” relations (Chi 1984; Reif 2008). Procedural knowledge is a part of metacognitive knowledge and contains knowledge about the usefulness of procedures in specific situations. Procedural knowledge here is limited to mean the methodological dimension of knowledge including especially the procedural nature of the experiments and model development which is needed to make connections between physics concepts and laws (article I) and it is achieved if the described procedure (experimental or modelling) is appropriate in the sense that it is performable, feasible or doable and correct from the physics point of view. Of course, only a written description of that procedural knowledge is accessible in the case of present study. Methodological knowledge is highly central in physics and here it means a methodical approach to acquiring, justifying and

using knowledge so that steps in the process can be followed and the acceptability and the performability of the steps can be assessed. In this sense, the choice of procedures is here traditional and the organisation of the knowledge in the maps reflects the way these procedures affect the ways the physics knowledge becomes introduced and organised in teaching.

4. Valid justification. Valid knowledge is justified and functional. Functional knowledge serves as the ability to re-organise the structure when new concepts are added into the network. The certain co-variation between concepts occurs, i.e. when one concept is changed or affected, other concepts become affected, too. This kind of interdependency has been argued to be an essential feature of dynamic, functional knowledge (Safayeni et al. 2005; Derbentseva et al. 2007). Functional knowledge is contained in the holistic relational structure, that is, what kinds of larger linkage patterns are formed in the concept map. Justified knowledge means skills to give ontologically correct, factually acceptable, and methodologically plausible arguments. Justified knowledge consists of logical argumentation so that stated claims (in the written explanation of the linking procedures) proceed in a sound order (cf. warrant of explanatory claims introduced by Sandoval and Millwood 2005). Justified knowledge in physics must be “true” in the sense that it gives real explanations to the real phenomena or observations. Justified knowledge is contained on written reports of the contents of the linking procedures. Students were asked to write down a short description of each experiment or model connecting two concepts. Their ability to give adequate justifications rests on the basis of commitment to evidence and critical thinking (Jiménez-Aleixandre and Erduran 2008). The valid justification can be identified as the logical order in which the argued facts are presented. In this thesis, the validity dimension is considered to be achieved if acceptable premises are used, and if methodology is adequately described and inferences about the results are discussed at some length. In summary, an argument follows *if-then-therefore* structure (Lawson 2009); or in other words, it includes *claim*, *evidence* and *reasoning* (McNeill and Krajcik 2007). Valid justification refers to the consistency and logic of the argument as it is connected to the aforementioned procedures.

These criteria form cumulative, hierarchical ladders and thus the numbering (1-4) tells the order in which the above epistemic “norms” should be fulfilled. It is evident that one first needs to know the ontological basis to be able to use the right facts. A relevant and useful methodology can be achieved if one has good command over the factual (or declarative) knowledge. It is emphasised here how factual or declarative knowledge, after all, forms the bedrock of more advanced forms of knowing. The valid justification is, in addition to plausible facts and methods, logical and sound. This method of analysis is developed to capture the student’s skills to produce valid justification, but also keeping in mind the desired properties of the good scientific argumentation, where epistemic acceptability is most central (for more details, see article III).

Within the network view the acceptability of knowledge is now understood so that if each individual link between concepts is acceptable and if the whole structure coheres (which requires enough acceptable connections), the knowledge system as whole represents acceptable knowledge. It is essential to note that in this approach the acceptability depends not only on the individual links, but essentially on the overall connectedness of the system. The relevant properties of knowledge organisation can be discerned from the empirical data consisting of concept maps by using the definitions of coherence (articles **I-IV**), contingency (article **V**) and acceptability of knowledge (article **III**) as it is summarised in sections 2 and 3.

4 EMPIRICAL DESIGN OF THE THESIS

The design principles explicated above were applied to construct concept maps during physics teacher education courses over the years 2006 to 2010. The author of the thesis acted as assistant teacher during the years 2006-2007 and as responsible teacher during the years 2008-2010. The research was thus closely connected to achieve the practical development of the courses to fulfil the requirements and goals of the pre-service teachers' education for the students taking physics as a minor subject. The concept maps were produced by students, who attended on the aforementioned courses in a teacher preparation programme. The courses were similar; of seven weeks' duration each and focused on questions concerning the conceptual structure of physics. In this thesis the concept maps made during the course in the context of electricity and magnetism are discussed. During the teaching sequence, the students first produced an initial concept map, and later, after instruction and group discussions, the final version of the map.

4.1 SAMPLE: HOW STUDENTS MAKE THE MAPS

Students produced the maps for purposes of teaching and the planning of teaching physics so that the level of the content corresponded closely to what is needed for teaching in upper-secondary school. In constructing the maps, the choice of concepts was restricted to a given set of elements, chosen to be either $n = 17$ or $n = 34$ the most important concepts and laws in the field of electricity and magnetism. The number of linking procedures was not restricted; they were only required to be either experimental or modelling procedures. The visual outlook of the maps is shown later (in chapter 5, Figure 2). It should be noted that students produced the maps in a rather advanced stage of their studies and hence they were familiar with basic physics and the basic concepts (all students had taken introductory level university courses in physics). Concept mapping as a learning tool to organise the content and to transform previous knowledge into a more functional form was already familiar to the students. The total set of concept maps gathered as the empirical data in this thesis consists of 78 maps. Of this set of maps, 66 were selected for closer scrutiny (remaining ones were too sketchy or limited by content), and eventually, a very thorough detailed content analysis was carried for 6 maps which had the most extensive content.

Students worked both individually and in small groups (about 2-4 persons in each). Each student constructed an own representation during lectures they had opportunities to discuss and compare maps in small groups. The

teaching sequence was planned in such a manner that first the students drew an initial version of the map and they got feedback from an opponent (i.e. another student's peer review). Students found the possibility for peer reviewing very useful since it advances also their own learning process. According to this feedback, students revised the map and often the changes were quite substantial. In addition to student-to-student feedback, also the instructor gave feedback and guided and helped during the whole construction process by asking conversational questions and justifications to tentatively drawn connections.

It should be noted, that each connection shown on the maps has required detailed discussions of the procedures creating the connection, whether the procedure is empirical or model-based, and how it can be justified. It is evident that in order to be able to concentrate on these demanding cognitive tasks, the tool needs to be flexible and easy to use, i.e. as invisible as possible. Therefore, most of the students used `CmapTools`-software to draw the maps and students usually had their laptops during lecture times in order to have a flexible opportunity to construct the maps by using `CmapTools`. In general, students found `CmapTools` an easy and helpful tool in organising knowledge.

4.2 QUALITATIVE FEATURES

The process of doing concept maps is meant to foster students' abilities in forming representations of physics knowledge and in organising it. Concept mapping is assumed to give a reflection of the students' knowledge structure but making these kinds of inferences from the maps is a challenging task for the evaluator. One possibility for recognising good organisation of knowledge is to pay attention to certain types of structural patterns. It has been suggested that both good understanding and the high quality of students' knowledge is reflected as large scale structures, which are tightly connected sets of several nodes and thus web-like (Kinchin et al. 2000, Kinchin et al. 2005; Safayeni et al. 2005; Derbentseva et al. 2007; Liu 2004). Such qualitative methods for analysing the concept maps have revealed that global topological features that are chain-, spoke- or web-like carry important information about the quality of knowledge represented in the maps. It is a plausible assumption that the structure of the relations expressed in a concept map is indicative of the richness and quality of the students' knowledge; a richer and more complex structure indicates better knowledge than a structure with very few and simple connections.

4.3 OPERATIONALISATION OF QUALITATIVE FEATURES

In order to visualise the relevant topological features, it is useful to make the visual appearance of the maps comparable by removing any ambiguity associated with the graphical layout. This can be done by redrawing the maps so that the same rules for ordering the nodes are used in all cases. In graph theory this is called embedding the graph. For the embeddings several well-defined methods are available. The embeddings used in this thesis were carried out using *COMBINATORICA* software (Pemmaraju and Skiena 2006). The embedded maps included the same information as did the originals (i.e. they were isomorphic representations).

Two different graph-embedding methods were used, both of which are standard visualisation methods used for network data (see e.g. Pemmaraju and Skiena 2006; Kolaczyk 2009). The first method was spring-embedding, which is obtained when each link is presumed to behave like a “spring” (i.e. the linear restoring force when distance increases) and then minimising the total energy of the spring system. The energy is minimised iteratively until a stable structure (i.e. minimum energy of tension) is achieved (for details, see Pemmaraju and Skiena 2006). The methods for representing the network as a “spring” network were chosen because linear forces are easy to handle, and because simple iterative schemes of energy minimisation are available (Kolaczyk 2009). Spring-embedding serves the purpose of revealing visually how tightly certain concepts are connected, so it is suitable for visual inspection of the clustering and cyclical patterns. The second form of embedding was tree-embedding (sometimes also called root-embedding). In tree-embedding, the maps are redrawn as an ordered hierarchical tree with a certain node selected as a root. The nodes and links are then rearranged so that the nodes, which are equidistant (i.e. the same number of steps is needed to reach each node) from the root, are on the same hierarchical level. The hierarchical levels thus contain all those nodes which can be reached with the same number of steps from the root node. Tree embedding is therefore suitable for inspection of the hierarchical organisation of nodes.

The structural features of a well-organised knowledge structure (i.e. hierarchical ordering and local clustering-like interconnectedness) are those essentially brought forward by qualitative analysis of concept maps (cf. Kinchin et al. 2000; Kinchin et al. 2005; van Zele et al. 2004). On the structural level, all these qualitative notions, which are based on visual inspection, need to be operationalised and made quantitative. In that, guidance was sought from network theory (Kolaczyk 2009). In order to measure how certain nodes (concept) cluster other nodes (concepts) around it, we have calculated several well-defined measures characterising the networks (for detailed definitions, see da Costa, Rodrigues, Travieso and Villas Boas 2007). The measures of most importance are (subscript indicates that the measure is for a node k locally):

1. Degree of node D_k which measures the number of connections (links) on a given node.
2. Clustering coefficient C_k , which measures the number of triangles and their connectedness around a given concept.
3. Subgraph centrality SC_k , which measures the number of subgraphs that constitute closed paths traversing through a given node.
4. Transit efficiency T_k , which measures the relative ease of passing through a given node and is a kind of modified inverse geodesic distance or the so-called efficiency in a network.
5. Hierarchy H_k , which measures degree of hierarchy and is calculated as a hierarchy level weighted sum of connections within a given level.

The hierarchy measure is thus very similar to that introduced by McClure et al. (1999) but now the scoring rewards of the number of levels (through weighted sum). One advantage of this hierarchy measure is that perfect tree-like hierarchy without intralevel connections will have $H_k=0$ while a fully connected structure with only one hierarchy level will have $H_k=1$. Sophisticated hierarchies, which are tree-like with a number of intralevel connections (typical to structures with cycles), will always have $H_k>1$. The mathematical definitions of the local measures of the topology are given in Table 1 (articles I and II).

Table 1. *Mathematical definitions of variables for measuring the topology of the concept maps. The subscripts k refer to k th node, the number of nodes is N , and the number of links M . The adjacency matrix is given by \mathbf{a} and has elements a_{ij} . The matrix of the shortest paths is \mathbf{d} (elements d_{ij}) and is obtained from hierarchical tree-embeddings. The tree-embedding, which begins from node k , also yields the number of hierarchical levels l_k with $n_k(l)$ cross links.*

Observable		Definition
Degree of node	D_k	$k_{i,in} + k_{i,out}$, k = number incoming/outgoing edges
Clustering	C_k	$\sum_{k>j} a_{ij}a_{ik}a_{jk} / \sum_{k>j} a_{ij}a_{ik}$, \mathbf{a} = adjacency matrix
Subgraph centrality	SC_k	$(\sum_k (\mathbf{a}^k)_{ii} / k!) / (\sum_j D_i / N)$
Transit efficiency	T_k	$(\sum_{j,k} (d_{ji} + d_{ik}) / d_{jk})^{-1}$, \mathbf{d} =matrix of shortest paths
Hierarchy	H_k	$\sum_j j n_j / (N - 1)$, j =hierarchy level with n_j cross links
Importance	I_k	$C_k \times SC_k \times T_k$

The observables in Table 1 give information of the different but closely related structural aspects of the concept network and they are therefore first calculated for each node in the network. It is found that coefficients C_k , SC_k and T_k more or less correlate, because they are measures of different aspects of the centrality of the node (concept) in the whole structure. This suggests that we can reduce the information by requiring that the node, which is structurally important and clusters other nodes around it, has a high value of all observables C_k , SC_k , and T_k and thus define the importance I_k of the node in regard to its clustering capability as a product (articles **I** and **II**). In practise, hierarchy and clustering are essential in describing concepts' centrality (articles **IV** and **V**) since importance I_k correlates strongly with clustering. In article **V** a simplified version of importance I was used, namely cohesion Ω . Cohesion gives very similar information as the importance I but can be operationalised more easily.

Once the bare structure of concept maps is made comparable it is possible to consider the quality of the linking procedures. In this mode of representation the four levels of epistemic justification are displayed as link weights from one to four. A combination of the bare structure (connections between concepts), and the grading of links is visually informative since the thickness/thinness of the linking arrows represents the quality/vagueness of the described procedure. This kind of representation instantly gives an overview of the drawn conceptual structure and which parts of it are well-justified and which concepts students do not manage to represent so well (see article **III**).

4.4 DATA MODELS FOR INTERPRETATION

The data (concept maps) also reveal other interesting features which can be discovered through the suitable modelling of data. These features include: 1) The quality of the student maps and its changes, which are linked to students' development in understanding the relational structure of concepts, discussed in article **IV**) ordering of concepts, linked to logic of progress in introducing the concept as conceived by students, discussed in article **V**. However, these aspects are not directly accessible from the structural analysis but instead, further data modelling is needed

4.4.1 CHANGES IN QUALITY

The quality of the concept maps can be defined through the topology of the concept maps. Since all links are procedural connections, based either on experimental or modelling procedures, richness of links simply represents the richness of the procedural knowledge that students have at their command. Defining quality q as a kind of latent variable related to the measurable variables of clustering and cohesion, it becomes possible to

quantify quality through multivariable data-model so that q depends on the average number of connections per node (richness of content, d) and on the average clustering and cohesion. How this is technically done is explained in detail in article **IV**. This data-model is used in monitoring changes in the concept maps consisting of two sets of maps (initial and final ones), made before and after a teaching sequence. Development of structure (defined with two variables, quality of structure, q or richness of content, d) can be interpreted as development in students' conceptual understanding by using Vygotsky's (1978) theory of the *zone of proximal development* (ZPD). Progression in both dimensions q and d is not easily reached. In moderate changes in either q or d , teaching promotes development of actions, which are soon developing. Thus, in co-operation and supervision (guided learning) students are able to solve more complex tasks than when solving them alone. Apparently in this case, improving either structure or content is possible, whereas improving them both overshoots ZPD. These aspects are discussed and rationalised in more detail in article **IV**.

4.4.2 CONTINGENCY AND ORDERING

The relational structure and ordering of concepts represented in concept maps is closely connected to the question of how to justify the introduction of new concepts on the basis of concepts which have already been learned, and how many different ways there are to do this. Then knowledge learned earlier is the basis upon which new knowledge is built. The concept maps made by the pre-service physics teachers represent not only the relatedness of concepts, but they also represent how concepts are introduced in teaching so that knowledge learned earlier is the basis upon which new knowledge is built. This means that, in a sense, these directed networks also represent the "flux of information" which pre-service teachers have planned to take place in their teaching. In well-planned teaching there should naturally be a regular flux of information (for evenly paced learning of new knowledge), but no unnecessary abrupt changes in that flux (otherwise the demand to assimilate new knowledge would vary much); moreover, uncontrollable reductions in the flow should be hindered (to prevent the impression that learned knowledge would not be needed in further learning). These aspects are discussed and rationalised in more detail in article **V**.

5 EMPIRICAL RESULTS

The concept maps produced by students are rather complex representations of the relations between concepts. Even a visual inspection already shows that the global structure is remarkably connected, but in such an ordered way that certain typical repeating patterns can be seen. These structural features (cycles understood as clustering-like interconnectedness locally and branches giving hierarchical ordering) describe the qualitatively defined requirements for well-organised knowledge structures. These are the features that have been essentially brought forward by qualitative analysis of concept maps (cf. Kinchin et al. 2000; Kinchin et al. 2005; van Zele et al. 2004).

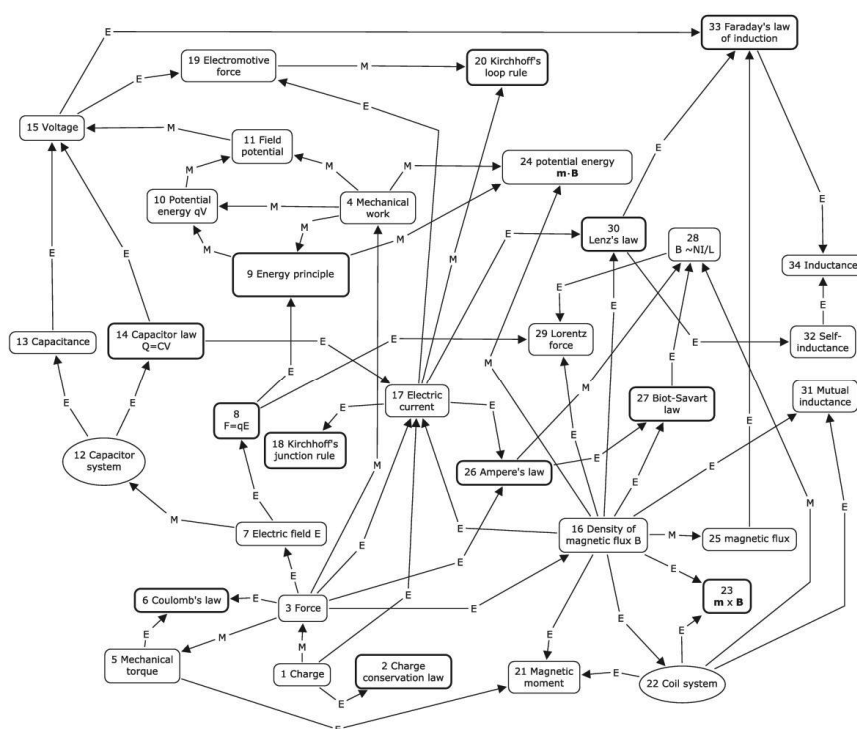


Figure 2 An example of a richly connected concept map having an average connectivity of 3.53 (i.e. the average number of in- and out-going links for each concept). Cycles and branches can be observed through the structure of the map. For example, a triangle can be found in potential energy, field potential and mechanical work, whereas the density of magnetic flux forms a strong branch.

The triangular cycles can now be seen in several places in the concept map in Figure 2. These cycles indicate the transitive-like connection between concepts when they are used in the context of either an experimental or a

modelling procedure. When such connections are repeated, the map acquires a set of internal connections, which locally follow similar types of patterns. This property can be associated with the structural coherence. When the connections are justified, this adds the aspect for epistemic acceptability of the connections on the existing structure; such a combination of structural coherence and epistemic acceptability can be taken to represent coherent knowledge. It is suggested here, that this kind of definition of coherent knowledge is well motivated from the point of view of structure and content, and moreover, it has the advantage that it can be operationalised.

5.1 QUALITY OF STRUCTURE

The quality of students' content knowledge can be connected to certain structural characteristics of concept maps, such as the clustering of concepts around other concepts, cyclical paths between concepts and the hierarchical ordering of concepts. A standard method to evaluate concept maps is to compare them to a "master map" (i.e. a map constructed by experts in the subject content, see Ruiz-Primo and Shavelson 1996).

In order to compare the students' concept maps with the above introduced master maps (denoted by MM), the total amount of information needs to be reduced. In order to do so, attention was paid only to I_k and H_k . The values of these quantities in the students' maps were compared to those in the master map by taking a "projection" of the variables. This is carried out by representing the variables as vectors X and calculating the projected value X_P of the variables as a scalar-product

$$X_P = (1/L)(X_{MM} \cdot X)^{1/2}; \quad L = (X_{MM} \cdot X_{MM})^{1/2}$$

where L is the normalisation factor chosen such that the projected values (length of the vectors) are the same for the original maps as for the master maps. The purpose of the comparison is to determine whether the concepts and laws in student maps have a similar structural position to that of the master maps. It is shown later that different concepts in the master maps then fall into different classes, making it clear that the hierarchy H_k and importance I_k are directly related to the content relevance of the concepts. The values of X_P close to 1 now require that the value sets of the variables be close to each other in both the students' concept maps and the master maps (i.e. the same concepts are in similar ways structurally important). A value of zero means that no structural similarities exist, or alternatively that structurally important concepts differ entirely from the master maps. Comparison on the basis of the projection has the advantage that, first the structural properties of interest (H and I) are defined and then they are compared on the basis of the corresponding structural variables. Then the structural analysis and the comparison both rest on the same theoretical

footing, which allows us to couple both the content and structure. This finally motivates us to define the quality of the map as the product $H_P \times I_P$. The details of this method are presented in articles **I** and **II**.

The main finding in articles **I** and **II** is that importance I_k and hierarchy H_k measure structurally different features, and therefore, nodes with a high hierarchy are not always the concepts with the largest clustering capability or which are central to several cycles. This feature is seen particularly clearly if each node H_k is plotted against I_k as shown in Figure 3.

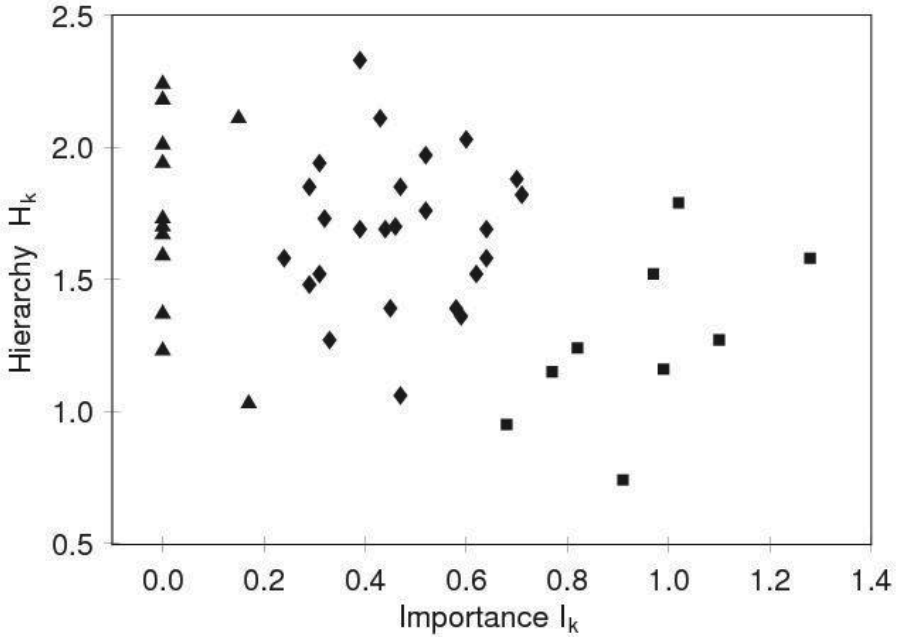


Figure 3 Hierarchy H_k plotted against importance I_k for each node k of the master map. Different clusters found by using agglomerative clustering analysis are indicated with different symbols.

The data for H_k and for I_k in Figure 3 can be grouped into three distinct clusters by agglomerative clustering analysis (Ruskeepää 2004). Three different distance criteria (Euclidean, Squared Euclidean and Manhattan) lead to exactly the same clustering as appears in Figure 3. The nodes are thus clustered into three distinct classes A, B and C on the basis of their roles in the topological structure of the maps. We can call these three classes clustering, hierarchy and connectivity classes. The clustering class consists of nodes of high importance ($I_k > 0.8$) but only moderate hierarchy ($0.7 < H_k < 1.8$) values. These nodes (concepts) are highly central for the map, but do not necessarily produce overarching hierarchies. The hierarchy class contains nodes with $1.4 < H_k < 2.9$, but with a low clustering capacity indicated by low values ($I_k < 0.2$). Nodes in this class thus produce the most extensive

hierarchical tree-like structures. The connectivity class gets its name from the notion that concepts in this class play a notable role in connecting several concepts to each other; they are equally clustering and hierarchically ordering, with $0.2 < I_k < 0.8$ and $1.0 < H_k < 2.3$ (article II).

The different concepts shown in the master maps thus fall into different classes, and hierarchy H_k and importance I_k together clearly provide a lot of information about the structure of the maps; moreover, they are also directly related to the content relevance of the concepts. The comparison of student maps to the master maps was carried out on the basis of the projection of the variables. The result was that the best student maps turned out to have very similar structural characteristics as the master map, and were thus well-connected and coherently ordered. However, several student maps lacked the high importance and hierarchy of concepts, and had very simple, chain-like structure.

The comparison with master map was an important intermediate step in developing the method and assuring its validity. The validity of the method is increased by the notion that the method produced results which are reasonable in the sense that experts produce maps with better characteristics than the students, and that there are clear distinctions between students maps.

5.2 EPISTEMIC ACCEPTABILITY AND STRUCTURE

The epistemic acceptability of knowledge represented in concept maps is closely connected to structural patterns presented in the maps. Different links forming the connection can be either well- or poorly justified. This is illustrated in Figure 4 where links are weighted according to their epistemic acceptability (compare with Figure 1).

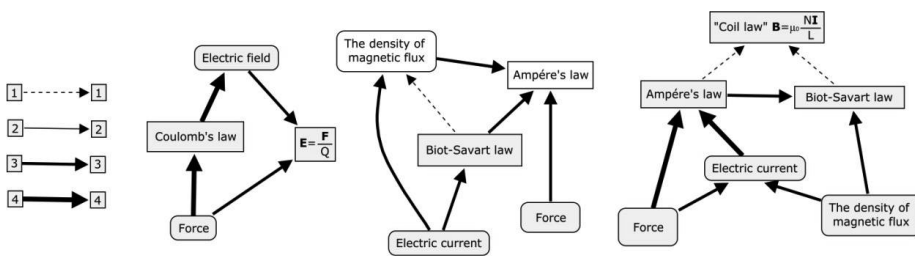


Figure 4 Examples of knowledge-ordering patterns and how they are affected when epistemic acceptability of links is taken into account.

As is shown in Figure 4, in the case of Coulomb's law, the links are well-argued and therefore its position in the structure remains as strong as it

would be in purely structural analysis. On the other hand, in that case, the structural elements are quite simple (just one cycle) and Coulomb's law itself is not clustering other concepts around it at all. Instead, the two other cases have more interesting features from the structural point of view. In the right-most case of Ampère's law the epistemic acceptability of all links is quite high. However, Biot-Savart law is not equally well-supported by other concepts. In this particular case, the student has misunderstood the meaning of the coil law and thus the reasoning is vague. In the middle case, Ampère's law and Biot-Savart law are equally well-justified, but the connection from Biot-Savart law to the magnetic field is poorly presented.

The epistemic analysis of links can be illustrated by redrawing the maps so that weights are explicitly shown. This format of representation reveals something of the functionality of knowledge; well-justified links are functional but poorly justified links cannot be properly used in the introduction of new knowledge. This approach gives an opportunity to evaluate quality of structure and the content of concept map on equal footing. In strongly connected (strong links) structure changing one part in it affects the whole network which means that it passes information effectively. Concept maps which are evaluated by their epistemic acceptability are illustrated in Figure 5. To make a clear presentation, the links fulfilling different epistemic criteria are drawn as individual pictures. In the first column from the left, all the ontologically acceptable links (epistemic criterion 1) are drawn with a bold line. In the second column, all the ontologically acceptable links which also present relevant factual knowledge (epistemic criterion 2) are drawn with a bold line. In the third column, in addition to ontologically and factually correct statements also adequate description of the used procedure is acquired (epistemic criterion 3). In the right-most column, the links presenting valid and sound justification (epistemic criterion 4) are drawn with a bold line.

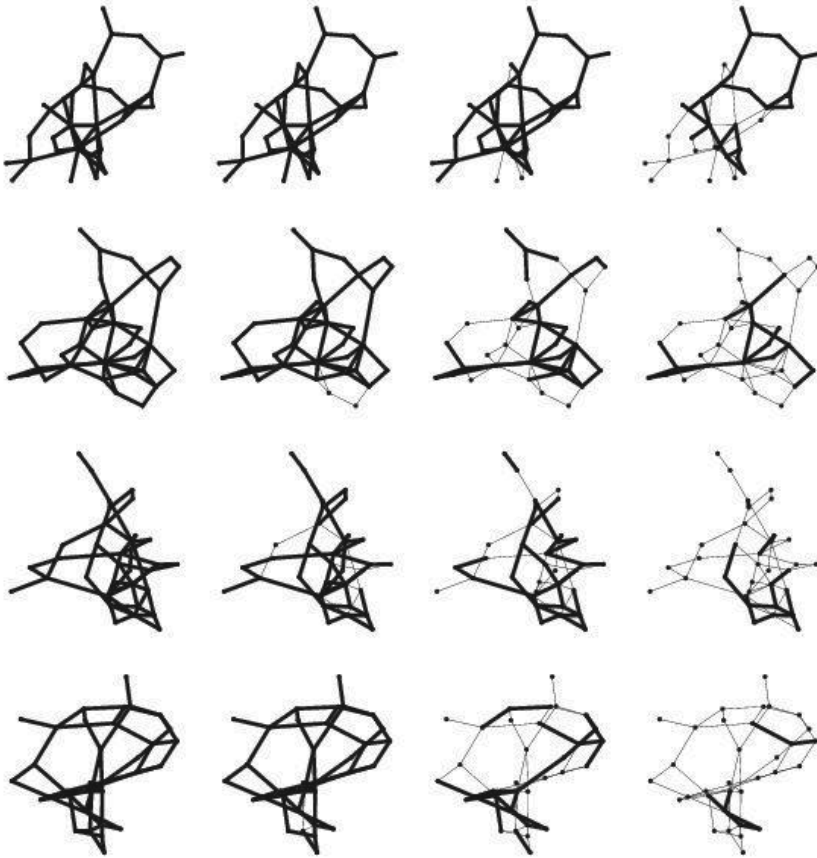


Figure 5 Weighted links for four different cases (concept maps). Note that each row presents the same map: the links with different epistemic level are presented as four separate webs. From the left to the right level: bold links presenting ontologically sufficient knowledge (1), factually acceptable knowledge (2), methodologically correct knowledge (3), and valid and sound justification (4).

The epistemic analysis visibly affects the structural quality of the maps. Weighting the links gives more information about the functionality and navigability in such network than the structural patterns alone. In none of the cases were there ontologically incorrect links and almost all links also present factually correct knowledge. Methodologically sufficient justification, on the other hand, seems to be more difficult to give and that level is not reached as well as the two first ones. Valid inference is, as supposed, most difficult and thus it is only given in some of the links. In general it is easy to see that in the first and second case the knowledge is presented more effectively when compared to other cases; lower epistemic level of knowledge is presented as most of the links are classified at the level of methodological

knowledge. Strong connections mean that the knowledge structure is well-justified and thus it is easy to navigate, meaning that knowledge is easily “reachable”. Such a consolidated structure seems, however, to be a demanding task for students to achieve, even though they admit its advantage in the usability of knowledge (article **III**).

5.3 DEVELOPMENT OF EXPERTISE: MODELLING OF DATA

The teacher’s expert knowledge results in retaining a good command of subject content knowledge and its structure. Thus, understanding the relational structure of physics concepts and how these can be reproduced in teaching is an important component in a teacher’s competence. As was discussed in section 4.4, the concept maps contain information indirectly of: 1) The quality of the student maps and their changes and; 2) contingency in ordering of concepts. These aspects become accessible through structural modelling of the data.

5.3.1 STRUCTURAL MODEL OF DATA

A structural model of the data, which allows us to predict the expected deterministic increase of the clustering and cohesion, is introduced in article **IV**. The analysis of the variations in the sample then allows detection of individual cases which are better than expected. These quantities can be used in classifying and monitoring the changes in the student’s concept maps, which represent the students’ ideas of the relations between physics concepts. This eventually enables the description of the structural quality (denoted by q) of the concept maps in greatly condensed form by using only one variable termed the structural quality and makes possible the monitoring of the students’ development on organising knowledge by using the maps (and thus supposedly also conceptual development) during the teaching.

In order to analyse the systematic dependencies and the variations around the mean the variables C (clustering) and Ω (cohesion) on D are regressed, but it should be noted that the dependence (regression) is not linear. The cohesion is very similar to importance and contains information of the overall connectedness and cyclicity. The cohesion is adopted here because it can be defined directly through the adjacency matrix (for details, see article **IV**). The regression means that the connectivity or the richness of content D is selected as an independent (or explanatory) variable, while the set $\{C; \Omega\}$ consists of the dependent (or response) variables. Such a structural modelling aims to condense the variables in a form of multivariate distribution $P(C; \Omega)$ which tells the frequency to obtaining a given set of values $\{C; \Omega\}$. This probability density function can then be used as the basis for defining the structural validity so that the values larger/smaller than the

average indicate structurally better/poorer than average maps. In practice, direct measure for that is given by the cumulative distribution function (CDF) $\Phi(C, \Omega) = \text{Prob}(P; C' < C; \Omega' < \Omega)$ of probability density function P in defining the structural quality in the form

$$q = \Phi(C, \Omega) - \Phi(0, 0)$$

The quality q then plays a direct role in interpreting how much the map with the given values of C and Ω deviate from the expected average map. Values $q < 0$ indicate structurally poorer than average maps while $q > 0$ indicates structurally better maps. Of course “structurally good” is then simply a statement that clustering and cohesion are all above average values, while “structurally poor” means that all values of structural variables are below average values. Similarly, “structural quality” refers only to these properties. The structural quality is completely independent of D and therefore q and d represent truly independent dimensions; structural qualities and richness of content. The quantities d and q can be used to monitor the change between initial and final maps. The differences can be formed $\Delta q = q_{\text{final}} - q_{\text{initial}}$ and $\Delta d = (d_{\text{final}} - d_{\text{initial}}) / d_{\text{final}}$, where Δd is scaled to give the relative change. These changes from the initial to final maps (in Figure 6) illustrate notable development of structure, and thus expectedly development in students’ conceptual understanding. The relative change in the richness of content (in x-axis) means that students have managed to integrate new content in their concept maps. The most important result is that most of the students are located in the right upper quadrant in Figure 6 which tells us these students really have made progress. There is a small group of students, which have reached substantial increase in richness of content but small changes in quality of structure. The results seem to indicate that it is not easy to perform well in both aspect (increasing the content and improving the structure) and that the most productive learning apparently takes place in the region where large changes of structure take place but changes in richness of content are moderate.

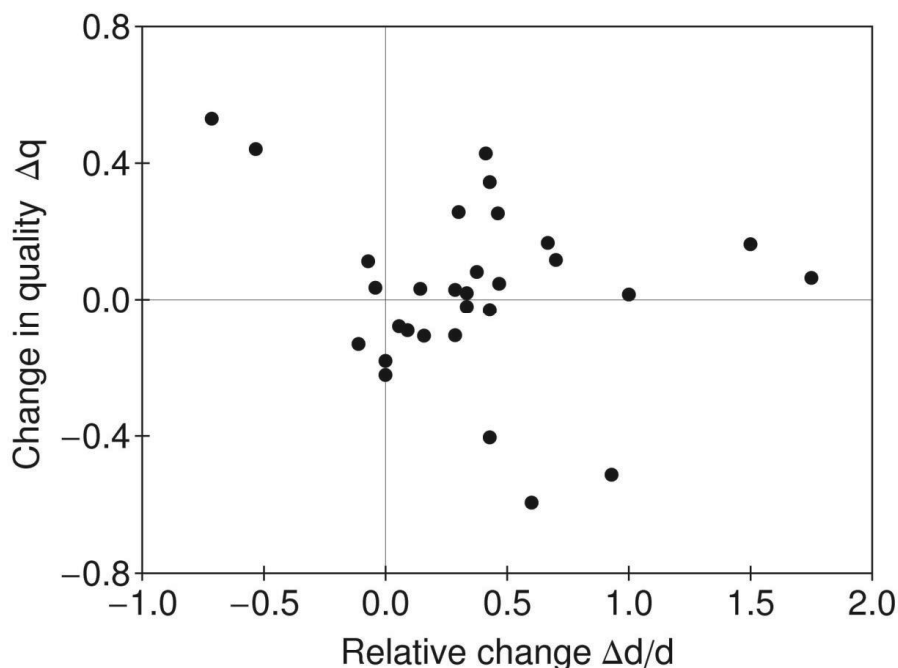


Figure 6 The change in quality in the concept maps with relative change of scaled degree d .

If there are large changes in richness of content, change in structure remains moderate or the structural quality can even become poorer as in the lower right quadrant. It might be that students have drawn the initial map in too optimistic a way (i.e. drawn with too many links, maybe based on a loose association) and realised afterwards that they are not able to justify all the links and thus have deleted some, with the result of a deteriorating structure. In some cases, located in the upper left quadrant students have apparently improved the structure simply by “pruning”, by reducing the richness of content in favour of better connected structures. Finally, the lower left quadrant represents cases where all has gone amiss – the content is impoverished and the structure has deteriorated.

The results show that in most of the cases positive development has taken place with either richness of the content, d , or quality of structure, q being improved. Progression in both dimensions q and d is not easily reached and it might well be too complicated a task for the students. The moderate changes either in q or d probably means that teaching and learning happens near the students’ *the zone of proximal development* (ZPD) as described by Vygotsky (1978). According to Vygotsky’s theory, teaching and learning is productive and meaningful if its goals are set so that they are a bit more

demanding than the goals easily achieved by the students in their starting position. In that case teaching promotes development of actions, which are soon developing, i.e. actions which are in the ZPD. Thus, in co-operation and supervision (guided learning) students are able to solve more complex tasks than alone. Apparently in this case, improving either structure or content is within the ZPD whereas, improving them both overshoots ZPD.

5.3.2 CONTINGENCY AND INFORMATION FLUX

The concept maps contain lot of information on the contingency of relations between concepts. In concept maps which have high contingency, it is possible to navigate through many paths from a given node to another node. Such contingency is related also to the “flux of information” which takes place in teaching. In well-planned teaching there should naturally be a regular flux of new information (in order that new knowledge is learned), but no abrupt changes in that flux (otherwise there are fluctuations in demandingness), and no uncontrollable reductions in the flux (which would give a feeling that learned knowledge is not needed in further learning). Therefore, the ordering of nodes, which comes from the ordering of the procedures, has a central role to play in determining the information flux. The fluxes Φ (flux into to the nodes) and Ψ (flux around the nodes) introduced in article **V** directly describe the “information” flowing from the previously introduced nodes to ones introduced later (Karrer and Newman 2009) and they are therefore, for our present purposes, the most important and interesting quantities.

Five cases of students’ concept maps are discussed in terms of the structural measures and the information fluxes. The information fluxes for master map and for one representative student map are shown in Figure 7. The case shown for a student map is typical in the sense that the features found in them can be also found in all similar, richly connected maps.

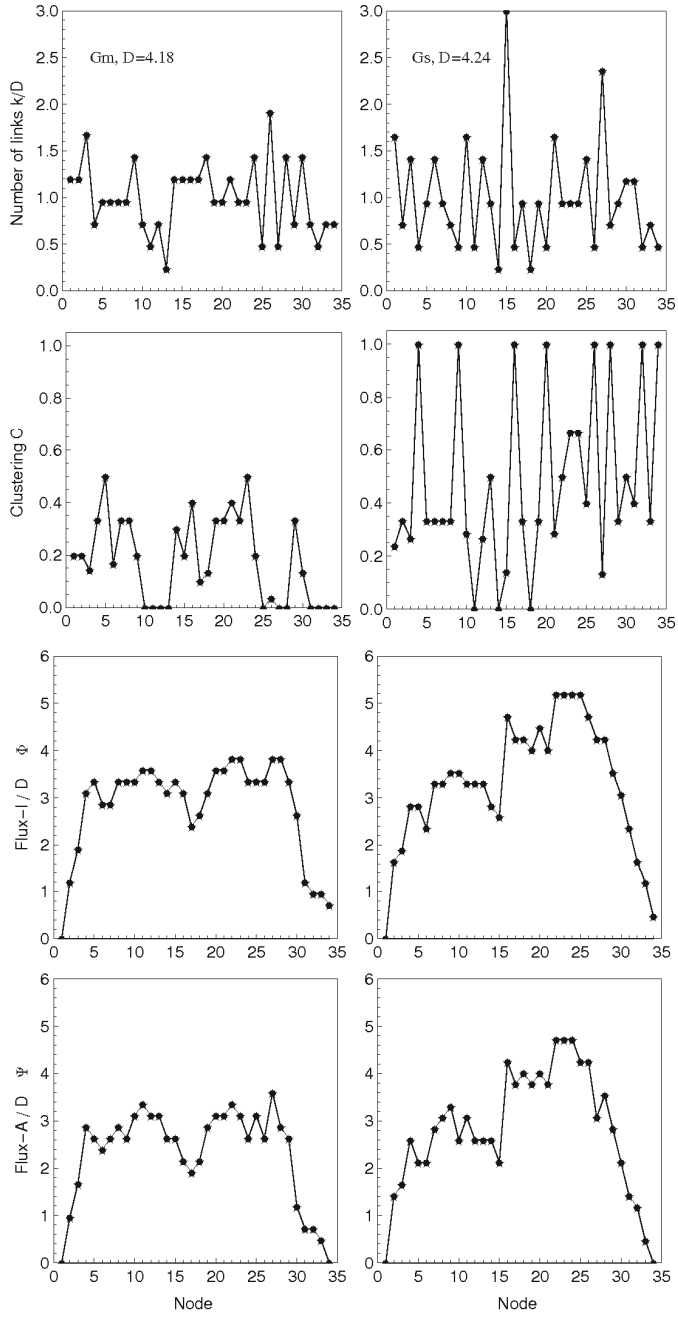


Figure 7 Node-by-node (nodes 1-34) values of degree D , clustering C , and fluxes Φ and Ψ . The first column shows the values for master map Gm and the second column for the student map Gs=G1.

The information fluxes are rather large in all studied cases. The results reveal that typically, per one link connected to a given node, there are from three to four links coming from the lower levels. This means that each node is rather well supported by the many previous nodes – the meaning content of the concept (node) is supported or backed up by knowledge contained on the network existing before the introduction of the new node. This, quite evidently, is one characteristic of well-planned teaching. In the sample of 70 maps there are, however, several maps which are nearly chain-like and very poorly connected with $D < 2$ and fluxes of order $\Psi \approx 1$ and $\Phi \approx 1$. In a well-connected network but poorly ordered or directed network, the fluxes would also be very small and the passage of information would be nearly hindered. In terms of the inherent logic of how concepts are introduced, this type of situation would indicate either: 1) circular reasoning, or 2) constant reference backwards. In clustering and the fluxes there are large node-by-node variations. The large variability from node to node indicates that there is a tendency for certain concepts to gather more links than other concept would do.

A suitable quantity characterising the relative variation is the dispersion of the variable defined as $\delta X = \sigma_X/X$, where X is the variable's average value and σ_X is the standard deviation. Interestingly, the dispersions for D , C and fluxes Φ and Ψ show that in student maps there is more variation than in the “master map”, which means that student maps are not as equally regular and balanced as the master map. This of course is related to the fact that in student maps there are abrupt changes in the information fluxes; some concepts become very central and much effort goes into their introduction. This, on the other hand, is somewhat awkward for teaching, because it means that the demandingness of learning may increase in an uncontrollable way. The master map does not feature such abrupt changes; instead, it displays a rather steady flux of information throughout the whole concept network. The results suggest that rich concept maps not only have large values of clustering and fluxes but, in addition, the node-by-node values do not vary much. This means that all concepts are roughly similar in the degree of importance for the whole structure. This, of course, is required from well-planned teaching, where most of the topics discussed should appear to be of importance for a student. Maintaining small node-by-node variability is relatively demanding, perhaps owing to the fact that it apparently requires evaluating the functionality of the structure as a whole instead of only locally.

6 DISCUSSION

This thesis addresses the problem as to how students' ideas of knowledge organisation can be approached and what approaches are available in making the important features of knowledge organisation visible. Two central aspects to which closer attention has been paid include conceptual coherence and contingency of pre-service teachers' subject matter knowledge. In order to make the coherence and contingency accessible, knowledge needs to be represented in a way which makes such features structurally visible. The empirical data used in this thesis are concept maps made by pre-service teachers because the concept map serves as an ideal representational tool.

According to diSessa (2008) and Thagard (2000) coherence needs to be related to the structure of knowledge and, this relation must be describable with certain structural characteristics of coherence. A similar notion holds also for contingency (BonJour 1985, see also Scheibe 1989). In this thesis, coherence is connected, on one hand, to the relations between concepts and, on the other hand, mutual dependencies between concepts (Thagard 2000). Contingency is also related to the mutual dependencies, but now in a way how dependencies are logically ordered and how many different ways there are to do it.

A coherent and contingent knowledge system which can be used to give explanations and make predictions of observed features of real systems carries the epistemic credentials of "true knowledge" (known as explanatory coherence, see Thagard 1992; BonJour 1985). Moreover, conceptual coherence leads to the idea that attention needs to be paid to basic knowledge-ordering patterns. Procedures of knowledge construction and processing may be simple ones even in those cases where the resulting structures are complex. Of particular importance are basic patterns, such as different types of hierarchies, cliques, transitive and cyclical patterns (Kemp, Perfors and Tenenbaum 2007; Kemp and Tenenbaum 2008). Knowledge structures presented in the form of concept maps provide possibilities in analysing the coherence of such a conceptual system.

In this thesis a new method is developed for analysing and evaluating the coherence and contingency of students' views of the relatedness of physics concepts. First, a method for structural analysis of concept maps is developed and suitable structural measures for coherent knowledge structures are introduced (articles **I** and **II**). Second, on this basis the analysis of epistemic acceptability of the knowledge structures is built (article **III**). The acceptability of links is analysed in terms of the four criteria set for epistemic analysis and it is operationalised by giving weight to each link. It should be noted that such epistemic analysis for an overall knowledge structure requires that the structure is specified first. The inspection of a concept map

supplemented by the epistemic analysis of links offers a transparent and in-depth method for evaluating knowledge which is represented in them.

6.1 ANSWERS TO THE RESEARCH QUESTIONS

The first research question (see chapter 3.1) is answered in articles **I** and **II**. The structural features that can be connected to the organised subject content are here found to be the coherence and contingency of knowledge structures. In this case, the coherence of the conceptual system depends on the acceptability of connections, and the norms of the acceptability are based on correspondence. On the other hand, the overall epistemic justification of the system and its parts depend on the overall coherence. Contingency of knowledge refers to how and in how many possible ways concepts are successively related to each other. In learning and teaching, contingency answers the question of how new concepts are introduced and justified on the basis of concepts which have already been learned.

The second research question is answered in articles **I-III** by introducing the new method which is based on representing the connectedness and relatedness of concepts as node-link-node structures in the form of concept maps. The structural measures for connectedness D , clustering C , hierarchy H , importance I and cohesion Ω are defined so that they directly measure the qualitatively identified structural features of well-organised knowledge structure. Hierarchical ordering and local clustering-like interconnectedness are those essentially brought forward by qualitative analysis of concept maps (cf. Kinchin et al. 2000; Kinchin et al. 2005; van Zele et al. 2004). On the structural level, all these qualitative notions are operationalised and made quantitative as shown in articles **I** and **II**.

The skeletal structure (node-link-node) forms the framework in which the acceptability of each link can be discussed by using the four criteria for epistemic analysis (article **III**). The analysis of linking procedures by weighting the links enables that the graphical structure is a reflection of contents dependence on structure. Such an analysis shows the fine-grained nature of epistemic justification and how students manage to present coherent knowledge. It turns out that the highest epistemic criteria are very demanding to fulfil and even at the advanced level only a fraction of students manage to reach this point. The results explicitly show how the degree of coherence becomes affected by the epistemic acceptability of links. However, the relation between acceptability and coherence is not linear, and even with a substantial number of low acceptability links, coherence may remain high. This shows the robustness of coherently connected conceptual systems.

The third research question is answered in articles **IV** and **V** through suitable modelling of data. Structural modelling of data defines a parsimonious set of variables which can be used to monitor changes in students' concept map structures, and furthermore, the change can be

interpreted as a development in students' conceptual understanding. The conceptual contingency represented in concept maps is approached from the viewpoint of how and in how many different ways the introduction of new concepts is based on concepts which have already been learned. This question is approached and answered in terms of the information flux. The contingency as it is revealed through information flux reveals clear variations in the sample, where the best students are the ones able to produce maps which show as steady and controllably changing information flux as a concept map made by experts.

6.2 VALIDITY AND RELIABILITY

The validity of the method of analysis and the subsequent results presented in this thesis hinges on the questions, as to whether the concept maps as representational tools allow expressing valid content, and if so, whether or not the structural measures correspond to the important and salient aspect of knowledge organisation. The first question is referred to as the content validity and the latter as the structural validity.

The content validity is to a large degree resolved by the notion that students need to justify each link and explain its (procedural) content in a written report coming with the map. These explanations are expected to contain correct physics and correct experimental or mathematical (modelling) methods. The epistemic analysis shows that although the depth and thoroughness of these explanations vary, they are always acceptable (i.e. correct models and experiments) from the point of view of physics content knowledge. Therefore, the number of links is directly related to the richness of correct content; more links means more valid content. On the other hand, the good structure is related to the ability to organise this content and good organisation requires that there are recognisable structural patterns. The most important patterns come in the form of triangular, cyclical and tree-like patterns. Because it can be argued that these patterns arise from different experimental and mathematical methods in acquiring and processing knowledge, the abundance of such patterns can be connected with good organisation and the lack of such a pattern with poor organisation of knowledge.

The structural validity of the analysis concerns the question of whether the variables provide information on the relevant structural aspect mentioned above. This question is answered by noting that degree D directly measures the richness of the content, whereas the structure is measured by the importance I of clustering and cyclicity and by hierarchy H . These variables are constructed so that they operationalise the qualitative structural features of interest. The close correspondence between the adopted measures with topological features solves the question of structural validity.

The reliability of the method is assured if it can be shown that the method, when applied in the analysis of the sample, produces reproducible results. For the structural analysis, this is assured because the method is an exact counting of defined structural elements. For epistemic analysis assuring the reliability is more delicate, because the analysis contains a component of interpretation. The analysis of epistemic acceptability was carried out by two interpreters for 20% of the data and an inter-rater agreement of 80% was achieved. This was taken to be enough for assuring a reasonable reliability of the interpretative analysis.

The remaining question is the reliability of the statistical analysis, concerning the statistical significance of the averaged values of variables (i.e. local variables averaged over the whole map). It has been shown in this thesis that the suitably scaled data can be described quite reliably by means of a multivariate normal distribution, which suggests that the residuals form a set of data, which is distributed independently, identically and normally, that is, it represents the so-called heteroscedastic data set, which has no internal bias. The possibility to have a data model, where the structural model describes the expected mean and the probability density P the deviations from the mean, forms the basis on which to attribute one quantity q to each concept map so that it describes the quality of the map in terms of the probability measure of the expected deviation.

On the basis of these notions it is concluded that the questions concerning the validity and the reliability of the method is adequately resolved and at least on the level that the most important conclusions are supported by the data.

6.3 IMPLICATIONS FOR TEACHING AND LEARNING

The main implications and practical uses of the work reported in this thesis have been in the development of pre-service teachers' education in the Department of Physics, University of Helsinki, during the years 2006-2010. Physics teacher education aims to foster the formation of organised knowledge structures which is often mentioned as being characteristic of expert-like knowledge (Chi, Feltovich and Glaser 1981). The practical problem in 2006, when the author of the thesis started as an instructor in pre-service physics teachers' courses, was to develop the use of concept maps as teaching and learning tools. The advantages of concept mapping and ideas concerning how they can be utilised in teaching physics are shared in many previous studies (Yin et al. 1996; Ruiz-Primo and Shavelson 1996; van Zele et al. 2004; Ingeç 2009).

The first challenge was to develop maps, which would allow representing complex knowledge. Concept mapping is known and widely used as a helpful tool for organising knowledge structures, but often the content of maps remains quite shallow. This challenge was met by developing the design

principles introduced here. Developing, testing and remodifying the design principles took place during 2006-2008. The relational structure between physics concepts can be presented by using procedural connections instead of traditionally used propositional links (articles **I** and **II**). These principles based on procedural rules may actually help students to achieve expert-level knowledge (cf. Kharatmal and Nagarjuna 2008).

The second challenge was to recognise those important features from the maps which revealed the students' abilities in representing and organising the knowledge. This challenge was met by developing the structural measures reported in this thesis. Although the measures as such have never been used in full-scale in grading and evaluating of the maps during courses (this would have been too tedious and time consuming), the method has heavily guided the practical grading and brought in much deserved clarity and objectivity. Now it is possible that two evaluators, paying attention to the number of links, triangular, cyclical and tree-like patterns can rather easily find agreement in the structural quality of maps in grading them. Previously, this seldom happened and different evaluators ended up with very contradictory evaluations.

Third, the epistemic analysis has been of similar practical use in formalising the criteria on how to evaluate the physics content contained in the links. The method for structural analysis of concept maps (articles **I** and **II**) has identified structural characteristics for well-organised knowledge structures. Structural analysis gives good scaffoldings but if done alone it is too shallow since it does not pay enough attention to the content. However, the whole knowledge structure (content and structure) can be only as good as its bare structure is. Now, this set of criteria is also used to instruct students on what aspect they should pay attention to in their argumentation. Based on the course feedback, although students found building up such qualified justifications quite demanding, they admit to its usefulness, too. Structural inspection of concept maps is supplemented by the epistemic content analysis of links which offers a more transparent method for analysing physics concept maps (article **III**). Moreover, the content analysis based on four epistemic levels is fine-graded enough to reveal interesting differences. Compared to the traditional method of analysing propositional knowledge represented in traditional concept maps, all the maps studied here would have scored very good points if scored by calculating the amount of appropriate links, level 1 and 2 (e.g. Novak and Gowin 1984; Ruiz-Primo and Shavelson 1996). However, when two more levels (3 and 4) are now taken into account, it is revealed that the highest epistemic level is very demanding to reach and only a fraction of students manage to have a good enough command on that aspect of knowledge.

Also, the concept maps represent the connections which are thought to be related to teaching, which also points to how information becomes introduced in teaching. Good and strong links mean good information flow, poor links indicate disruptions in the flux of valid and justified information.

These strengths or weaknesses of the basic structure are important for practical teaching, because they are a prerequisite of good teaching.

On the basis of the experience reached in our own teacher education experience, it seems safe to argue that adopting a similar approach can help teacher educators in their attempts to foster such good understanding of subject content knowledge which is required from professionally competent teachers.

7 CONCLUSIONS

An overview of the coherent knowledge represented as concept maps in physics teacher education is discussed in this thesis. New design principles and analysing methods are suggested in such a manner that concept maps are made useful in organising physics knowledge and whose characteristics for coherent and contingent knowledge are identified and defined. The suggested design principles based on procedural rules, which are the basic procedures to form new concepts in physics, actually help students to achieve expert-level knowledge. The approach discussed here is informed by the recent cognitively oriented ideas of knowledge organisation around basic knowledge-organisation patterns and how they form the basis of more complex concept networks. The new method generalises and widens the existing approaches which use concept maps in representing learners' knowledge, and which also use concept maps for research purposes. The method for producing the concept maps discussed here has been in use in physics teacher education for some time and according to what has been observed, students have well noticed the advantages of concept maps for visualising complex conceptual connections.

The cases examined here show that even in the advanced level of studies, the knowledge structures are still somehow fragmented and the overall justification skills are not as organised as they could be. The links are quite plausibly justified, but they do not build up a consolidated overview of this subject matter. The results of the thesis provide a new method to monitor the students' advancement in their skills in introducing new concepts in physics teaching and in building the convincing justification schemes for the purposes of teaching and the planning of teaching. The structural characteristic and the accompanying epistemic levels of justification, and how they interplay in order to produce well-justified knowledge-ordering patterns, also provide the means to define and recognise the organised knowledge, and to make it transparent how such organisation becomes established.

The analysis of maps and the positive results which show that students manage to organise their knowledge so that the epistemic requirements are fulfilled shows that from an instructors' point of view the goals are reached. The student feedback shows that students themselves also noted the advantages and their development in knowledge organisation, and the role of maps in facilitating it. This, of course, is important for self-reflection and meta-cognition. With this kind of deeper understanding of what the organisation of knowledge might mean and how it will be recognised, educators and instructors are better equipped to foster and also to monitor learning, which aims at supporting the formation of well-organised and ordered knowledge structures in teacher education.

The methods suggested in this thesis provide a novel approach for monitoring the students' advancement in supporting the knowledge and in building the convincing justifications. The analysis on structural characteristics and epistemic acceptability, and how they interplay in order to produce well-justified knowledge-ordering patterns, provide also the means of defining and recognising the coherence of knowledge, and to make it transparent how such coherence becomes established. With this deeper kind of understanding of what the coherence of knowledge might mean and how it will be recognised, educators and instructors are better equipped to foster and also to monitor learning, which aims at supporting the formation of well-organised and ordered knowledge structures in teacher education.

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